GLASS-MELTING FURNACES

UDC 666.1.031.2

GLASS MELTING FURNACES DESIGNING ENERGY-EFFICIENT BOTTLE GLASS FURNACES

V. Ya. Dzyuzer[1]

Translated from *Steklo i Keramika*, No. 9, pp. 5 – 9, September, 2008.

It was shown that developing an energy-efficient design for a bottle glass furnace implies the use of modern design methodology. It is necessary to include mathematical modeling before the technical design stage in the structure of the traditional stages of work on a furnace design. The boundary conditions of modeling must reflect the conjugate character of external and internal heat exchange and the hydrodynamics of the melting tank.

The domestic glass container industry is now developing in conditions of a global increase in prices for fuel and energy and raw material resources. Some glass works have entered a period in which technical inefficiency of production unambiguously predetermines economic failure. Thermal energy has been irrationally used in domestic glass melting for decades. The low thermal efficiency of glass-melting furnaces is a problem that must be solved in order to remain in the modern market of manufacturers of glass articles. The situation is now such that the possibility of evolutionary development of the enterprises is actually over. The revolutionary approach related to large expenditures of financial resources primarily involves a change in the mentality of the workers in the industry and design organizations, whose interaction is graphically represented by a conceptual design model (Fig. 1) [1].

It is unconditionally the prerogative of the industrial enterprise to define the goal of the design. The problems that arise during subsequent operation of the furnace are usually related to the rushed and/or unsatisfactory study of this design stage. Continuous use of glass-melting furnaces makes it impossible to update them during periods between servicings. For this reason, in determining the goal of a new design, it is necessary to foresee market trends and the possibility of remaining competitive for the entire lifetime of the furnace.

With respect to glass-melting furnaces, defining the purpose of a new design implies solving a Multivariant problem with a large number of variables [2]. Let us separate out the main problem — the heat rate for glass melting and removal of the glass melt from 1 m^2 of glass tank area per furnace campaign. In countries with a developed glass industry, the heat rates for melting bottle glass are on average 5.0 MJ/kg and in the best furnaces, 4.3 MJ/kg. For the second index, the level attained in production is approximately 8000 tons/m^2. In defining the technical parameters of a design, the budget for constructing the furnace is most important. In this respect, it is pertinent to recall that attempting to minimize costs inevitably results in a compromise whose resolution should not affect the thermal efficiency of the furnace.

Let us turn to the problem of the knowledge necessary for developing designs suitable for the world technical level. The complexity of modern glass-melting furnaces does not allow using traditional design methodology based on theoretical knowledge and practical experience in operating low-output aggregates with a high heat rate. An up-to-date data base for designing energy-efficient furnaces with high spe-

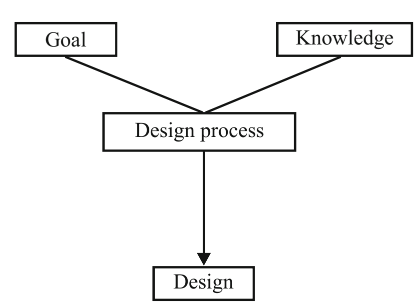


Fig. 1. Conceptual design model.

[1] Ural State Technical University – UPI, Ekaterinburg, Russia.

0361-7610/08/0910-0296

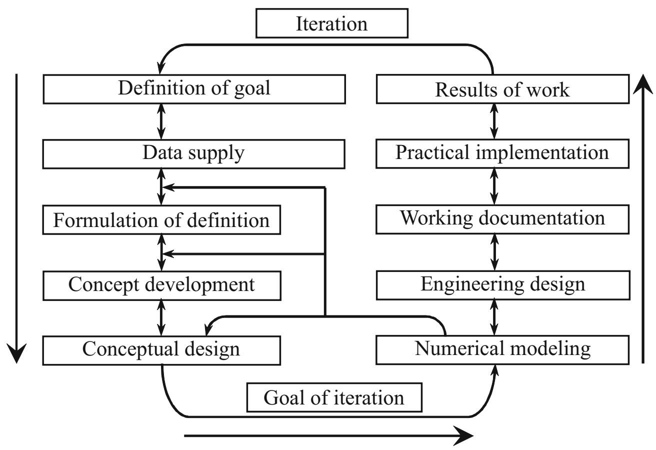


Fig. 2. Stages of the design process.

cific output is formed based on the results of mathematical modeling of heat and mass exchange processes that take place in the flame space and melting tank [3, 4]. Problems of this kind of complexity can be solved by using a conjugate model of heat exchange and hydrodynamics adapted to the conditions of operation of high-output furnaces [5]. Numerical modeling of the furnace with definition of real boundary conditions both with respect to its geometry and with respect to the operating parameters is a necessary condition of contemporary design [6 – 9]. In contemporary methodology (Fig. 2), the modeling stage follows the conceptual design and precedes the technical design stages [10].

The modern approach to designing glass-melting furnaces even makes it possible to obtain important applied results in partial modernization of a furnace [11]. In developing new furnace designs (without using additional electric heating), the specific output of glass melt of composition ZT-1 reaches > 2.5 tons/($m^2 \cdot$ day) and the specific heat rate for glass melting is 4.5 mJ/kg, which corresponds to the parameters of modern glass-melting furnaces [12]. Using a data base on thermophysical aspects of glass melting increases the quality and conceptual design. The basic energy characteristics of the future furnace are determined in this stage. The results of modeling such aggregates can be used to compile an initial data base for calculating the heat balance of the furnace prior to the conceptual design [13, 14]. On the whole, we can say that use of modern design methodology (see Fig. 2) produces more substantiated design solutions. It becomes possible to correctly test (for correspondence to physical laws) the effect of most design and operating parameters of the furnace on its operating indexes.

The correspondence of the engineering solutions to the stated design goals is relatively simple to assess based on an analysis of heat-balance items. We will use the data in [14], where the heat balance of a bottle glass furnace with output of 240 tons/day is reported. The design of the furnace is characterized by calculated values of the efficiency of 57.7% and heat rate for glass melting of 4.42 MJ/kg. At a furnace heat load of 12.2876 MW, the input part of the heat balance (18.885 MW) is formed from the chemical heat of the fuel (65.06%) and from the physical heat of the preheated air (34.85%) and fuel (0.09%). In the throughput part, we distinguish the effective expenditures of heat (37.55%), losses with combustion products (42.20%), and overall losses of heat to the environment (8.24%).

TABLE 1

Furnace construction element	Average heat losses, kW/m^2	Specific heat flow, W/m^2
Roof	1.8	1160
Flame space:		
long walls	5.4	1150
Long walls	1.8	1220
Glass-melting tank:		
bottom	1.3	800 – 1500
side walls	5.6	1000 – 1200

The structure of the heat balance item gives a clear notion of the distribution of thermal energy in the modern glass-melting furnace. First of all, consider the important decrease in heat losses to the environment, whose value is more than 2 times lower in comparison to the traditional design execution of hot and cold linings for the design execution branch [15]. Only 5.27% goes directly for losses by thermal conduction through the furnace lining. Approximately 2.07% comprise losses of heat through forcibly cooled (air flow rate of 20 m/sec) of a section of the outer surface of the melting tank. So-called design energy losses (0.9%) through the mouth arches, loading pockets, and viewing windows are significantly minimized. A cautious approach to designing the refractory and heat-insulating lining of the flame space and melting tank [16, 17] allows obtaining low enough heat losses through all design elements of the furnace. The heat losses through the design elements of the melting part of a glass-melting furnace [17] are characterized in Table 1.

We should recall that minimization of heat losses to the environment should not be reflected in the operating conditions of the refractory lining of a furnace. For this reason, it is necessary to have information on the temperature distribution on the surface of all design elements of the flame space. This is especially important for a horseshoe-shaped scheme of movement of combustion products where asymmetric input of fuel relative to the longitudinal axis of the furnace initially creates highly uneven temperatures in the gaseous medium and safety heating surfaces. The presence of lining sections with a local temperature much higher than the safe level for refractory material is the appearance of this nonuniformity in incorrect assignment of the extent of the fuel combustion zone (flame length). The temperature distribution over the surface of the glass melt and roof is especially important. In the first case, it is necessary to know the posi-

tion of the thermal quell point and its correspondence to the technologically caused interface of the convective flows of the pouring and production cycles. Second, only the distribution of the average temperature over the width along the length of the flame space allows determining the longitudinal coordinate of its maximum, i.e., the site of installation of a thermocouple for controlling the thermal work of the furnace. The value of this coordinate (in the ideal case) should correspond to the given position of the thermal quell point.

We know that the analytical and balance methods of calculating external heat exchange do not allow solving this level of problems. For this reason, an applied analysis of the external heat-exchange problem can only be executed by numerical modeling [3]. In the last 20 years, the problems of flame organization and external heat exchange on the whole have fallen off the radar of scientists and workers in the domestic glass industry, and a clear world trend toward an increase in the specific output of the furnaces and a decrease in expenditure of thermal energy for glass melting was formulated in this period. Insufficient attention to the problem of heat generation in glass-melting furnaces logically led to a state where heat outlays for glass melting in the sector are 1.5 times higher than the world level.

We note that a correct study of heat and mass exchange processes implies a combined examination of the external and internal problems. As the results in [3 – 7] show, they can be combined with respect to the surface of the melting tank. In this case, in solving the external problem, boundary conditions of the second kind are defined, which allows considering the differentiated distribution of expenditures to glass formation and heating of the glass melt through the source term of zonal equations in solving the external problem on the surface of the glass melt. In modeling internal heat exchange and hydrodynamics, the solution of the external problem in the form of the temperature field on the melt surface is one of the most important boundary conditions for heat and mass transfer in a melting tank.

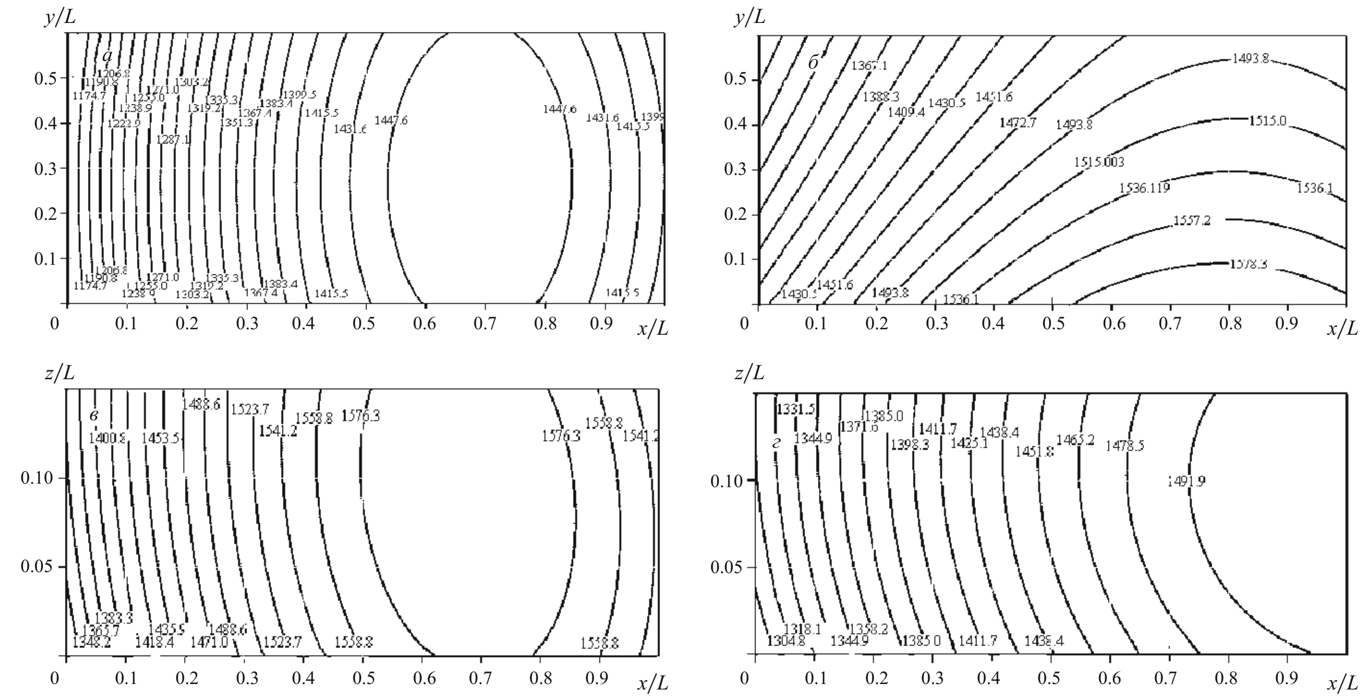
In practical glass melting, control of the completeness of fuel combustion is the basic parameter for assessing the efficiency of the combustion process. The extent of the combustion zone is considered as a variable characteristic whose value is obtained from a visual evaluation of melting of the batch on the surface of the glass melt. The reaction to slowed melting is reduced to shortening of the flame. The appearance of foam in the pure surface zone is suppressed by increasing the length of the intensive combustion zone to a size at which the luminous part of the flame can act on this section of the surface of the melt. Such an approach to the most important characteristic of the combustion process is based on not understanding the effect of the flame length not only on external heat exchange but also on the hydrodynamics of the melt.

The results of modeling the combined problem of heat and mass exchange suggests that the optimum flame length should be equal to the length of the flame space of the furnace in a glass-melting furnace with a horseshoe-shaped flame direction. For visually assessing the combustion process, the length of the luminous part of the flame can be used and should not exceed 70% of the length of the flame space [6, 7]. Deviation of the real flame length from the optimum value creates grounds for local overheating of the refractory lining and by changing the boundary conditions on the surface of the glass melt, perturbs the convective field of the melt. A periodic change in the boundary conditions on the surface of the melt destabilizes the structure of convective flows. The result of such perturbations is worsening of the quality of the finished glass.

The effectiveness of external heat exchange in the flame space of a furnace implies not only optimization of the flame length but also implementation of the other requirements imposed on its organization. First of all, it is necessary to ensure flat movement of combustion products relative to the surface of the glass melt. We know that the position of the flame in the flame space is determined by the burner design and the air and fuel jet rate characteristics. It is necessary to consider that the design features of the furnace with a horseshoe-shaped flame direction limit the angle of attack of the flame in comparison to the transverse heating scheme.

The data in Fig. 3 were obtained for a furnace with unit output of green glass melt of 2.6 tons/($m^2 \cdot$ day). They indicate that optimization of external heat exchange allows obtaining a temperature distribution on the heating surfaces corresponding to the conditions of safe operation of a furnace with a Dinas roof. The temperature of the outgoing heating products (1450°C) is sufficient for high-temperature preheating of air (1250 – 1300°C). The requirements for the regenerator design and materials which would ensure that these temperatures are attained are reported in [18]. The temperature fields presented in Fig. 3 are a visualization of the corresponding two-dimensional equations approximating zonal calculation data. An analysis of these equations allows determining not only the local value and coordinates of the maximum temperature but also the coordinates of the placement of the roof thermocouple and thermal quell point.

The necessity of stabilizing heat and mass exchange in the melting tank is the most important requirement for organizing the thermal work of a glass-melting furnace. Its practical execution implies not only optimization of external heat exchange but also respect of other conditions related to the process features of glass-melting furnaces. The results of modeling the internal problem in [8, 9, 12] indicate that the established concept of the role of the temperature distribution on the surface of the glass melt in conditions of operation of high-output furnaces does not completely correspond to practical reality. We first note that the position of the thermal quell point, which determines the melt flow picture in natural convection, should coincide with the optimum length of the luminous part of the flame. In the presence of powerful production flow (for example, 3.47 kg/sec), conditions are created in the melting tank for the appearance of forced convection. The boundary conditions for forced convection are



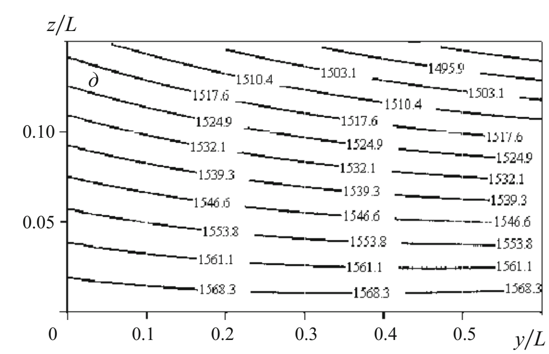


Fig. 3. Temperature field on the surface of glass melt (*a*), roof (*b*), long [*c*, *d*) heated and deflecting sides of furnace], and end walls (*e*): *L*) length of flame space; *x*, *y*, and *z*) its coordinates for length, width, and height, respectively.

not only determined by the specific output of the furnace but also the conditions of loading and melting the batch and the site where the melt is taken off for production.

When glass is not being produced, the structure of the convective field of the melt is determined by the free convection characteristics. As a result, two local differently directed convective flows whose interface coincides with the position of the thermal quell point are formed in the longitudinal section of the melting tank. Switching on the mechanism of forced convection transforms the classic flow structure. As a result, a convection field is formed where the size of the local circulation contours and the direction of the medium do not correspond to the characteristics of natural convection. The statement that differently directed convective flows in the pouring and production cycles are observed in the tank of an operating furnace has not been experimentally confirmed. The difference in the results of modeling and the existing concept concerning the hydrodynamics of the melt is probably due to the fact that the latter were obtained for glass-melting furnaces with low specific output. On the practical level, it is important to emphasize the necessity of a more rigorous attitude toward the change in furnace output during its operation. A difference between the output and the nominal value could significantly transform the picture of the melt flow and temperature field in the tank.

Creating conditions for formation of pronounced convective flow in the left part of the tank with counter-clockwise rotation of the medium is the most important melting tank design function. The circulation ratio in this circuit is of primary importance for heat transfer and the residence time of the melt in the tank. The higher the melt circulation ratio in the pouring circuit, the more positive the effect of design innovations on internal heat and mass exchange. The temperature of the melt near the surface of the tank on the axis of the loading hopper is an objective quantitative characteristic of the convection picture in the primary batch melting zone.

Heat and mass exchange in the right part of the tank is determined to a significant degree by the position of the neck and the output of the furnace. At the same time, improvement of melting tank design should be reflected in rationalization of convective flow in the output cycle. In the process aspect, two basic requirements can be the basis for an evalua-

tion of this convective flow. They concern the residence time of the melt in a given part of the tank and the thermal homogeneity of the glass taken off in output. In comparable conditions, both characteristics are determined by the circulation ratio of the medium in this circuit.

The following must be done to objectively evaluate the effect of melting tank design elements on internal heat exchange and melt hydrodynamics, together with an analysis of the overall picture of flow of the glass melt in the long section of the tank:

an analysis of convective flow in the pouring cycle, including an evaluation of its size, ratio and direction of circulation of the medium, temperature distribution in the long section of the left part of the tank, and the change in the temperature near the surface of the glass melt, for example, on the axis of the loading hopper;

an analysis of convective flow in the output cycle, which provides for determining the average temperature of the glass melt entering the neck and its thermal homogeneity coefficient; it is necessary to recall that the temperature of the glass melt going out of the melting tank is the fundamental boundary condition for calculating and designing the production channel.

Correct design of the melting tank is thus inconceivable without numerical modeling of the internal heat exchange and hydrodynamics of the melt. The results of modeling, presented in the form of the temperature distribution and relative current lines in the long section of the tank, make it possible to evaluate the technical acceptability of the melting tank design [8, 9].

In conclusion, note that the contemporary approach to glass-melting furnace design can only be implemented within the framework of methodology that provides for mandatory mathematical modeling of the object. The modeling boundary conditions must not only take into consideration the furnace geometry but also the thermophysical and process aspects of continuous glass melting.

REFERENCES

1. V. Ya. Dzyuzer, V. S. Shvydkii, and A. S. Shishkin, in: *Introduction to Automated Design: A Handbook* [in Russian], Izd. UGTU – UPI, Ekaterinburg (2007).
2. V. Ya. Dzyuzer, "Improving the specifications of glass-melting furnaces," *Steklo Keram*., No. 7, 3 – 12 (2008).
3. V. Ya. Dzyuzer, V. S. Shvydkii, and V. B. Kut'in, "A mathematical model of a glass-melting furnace with a horseshoe flame," *Steklo Keram*., No. 10, 8 – 12 (2004).
4. V. Ya. Dzyuzer and V. S. Shvydkii, "A mathematical model of the hydrodynamics in the melting tank of a glass-melting furnace," *Steklo Keram*., No. 1, 3 – 8 (2005).
5. V. Ya. Dzyuzer and V. S. Shvydkii, "Methodology for adapting a combined mathematical model of hydrodynamics and heat exchange in a glass-melting furnace with a horseshoe flame," *Steklo Keram*., No. 12, 7 – 11 (2006).
6. V. Ya. Dzyuzer and V. S. Shvydkii, "Effect of the flame length on external heat exchange in a glass-melting furnace with a horseshoe flame," *Steklo Keram*., No. 7, 3 – 7 (2005).
7. V. Ya. Dzyuzer and V. S. Shvydkii, "Effect of flame length on the hydrodynamics of the melting tank in a glass-melting furnace with a horseshoe flame," *Steklo Keram*., No. 9, 5 – 11 (2005).
8. V. Ya. Dzyuzer and V. S. Shvydkii, "Effect of the overflow threshold on the hydrodynamics and heat exchange in the melting tank of a glass-melting furnace with a horseshoe flame," *Steklo Keram*., No. 7, 6 – 12 (2006).
9. V. Ya. Dzyuzer and V. S. Shvydkii, "Effect of melting tank design on heat exchange and melt hydrodynamics in a glass-melting furnace with a horseshoe flame," *Steklo Keram*., No. 10, 9 – 16 (2006).
10. V. Ya. Dzyuzer, "Methodology of glass-melting furnace design," in: *Proceedings of the II International Congress "Furnace Tube Design: Thermal Conditions, Design, Automation, and Environment"* [in Russian], Ekaterinburg (2006), pp. 119 – 128.
11. V. S. Meshka, V. I. Ureki, and V. Ya. Dzyuzer, "Experience in revamping the glass-melting furnace," *Steklo Keram*., No. 5, 17 – 20 (2007).
12. V. Ya. Dzyuzer and V. S. Shvydkii, "Numerical modeling of thermophysical processes in glass-melting furnaces," in: *Proceedings of the III International Congress "Furnace Tube Design: Thermal Conditions, Design, Automation, and Environment"* [in Russian], Ekaterinburg (2008), pp. 46 – 76.
13. V. Ya. Dzyuzer, "Improvement of the method of calculating the heat balance of a regenerative glass-melting furnace," *Ogneup. Tekh. Keram*., No. 3, 24 – 31 (2006).
14. V. Ya. Dzyuzer, "Improving the method of calculating the heat balance of a regenerative glass-melting furnace (conclusion)," *Ogneup. Tekh. Keram*., No. 4, 22 – 27 (2006).
15. A. S. Kozlov, *Heat Engineering of Regenerative Glass-Melting Furnaces* [in Russian], Legprombytizdat, Moscow (1990).
16. V. Ya. Dzyuzer, "Designing the refractory lining of the melting tank in high-output glass-melting furnaces," *Ogneup. Tekh. Keram*., No. 8, 14 – 22 (2007).
17. V. Ya. Dzyuzer, "Refractories for the melting part of glass-melting furnaces," *Ogneup. Tekh. Keram*., No. 5, 24 – 32 (2008).
18. V. Ya. Dzyuzer, "Refractories for the glass-melting furnace regenerator," *Ogneup. Tekh. Keram*., No. 6, 23 – 26 (2008).